The Ability to Switch Frames of Reference, and Its Relation to Mental Rotation

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Abstract

Many studies explore the differences between Route and Survey perspectives used in navigation and verbal directions, some of which examine the costs of switching between perspectives, as well as factors that mediate those costs. In addition, studies provide evidence for the role of different visuo-spatial skills involved in a range of navigation and map tasks, although none have looked specifically at visuo-spatial skills involved in the process of switching. This study tests for a correlation between mental rotation and the ability to switch between route and survey perspectives, by looking at performance and reaction times on a perspective-switch task, and examines the issues involved in a change between perspectives in a reading task. The stimuli in the reading task were adapted from previous studies, and altered to remove suggestions of other frames of reference, limiting the description to one perspective on the described location. The test revealed significant correlations between mental rotation and perspective switching through reaction time on a switch question, which differed significantly from the average response time, and through performance on questions after a route description by males. In addition this study catalogues strategies used by men and women on the mental rotation task, which may contribute to the gender difference found in the result as well as on the mental rotation task. The results, along with additional observations obtained during the study, are discussed in the context of reference frame types, to further explore what a reading-based, perspective-switch task entails.

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Introduction

This project explores the issue of perspectives employed while navigating, and the necessary transitions between route and survey perspectives, testing for a correlation with mental rotation skills.

It has been hypothesized that people have an innate ability, arising at a certain age, termed "representational insight," constituting an intuitive understanding of symbolic artifacts, including maps. This understanding involves grasping a correspondence between information presented in different perspectives: an object with an internal structure that one can manipulate - the map, and a 3-dimensional world in which one is immersed. Any map use requires a similar process of using knowledge from multiple perspectives, a process which is not well understood. This project explores the question of how people switch between route and survey perspectives, in the context of navigation. Its aims are to review literature incorporating different fields related to this problem, to contribute results from an experiment that build on past studies, and to discuss the results in the context of reference frames, to explore what a switching task entails.

The Background includes an overview of maps' contemporary relevance, and recent developmental and anthropological studies bearing on the question of representational insight. Next, a summary of perspective and frame of reference in a linguistic and philosophical context serves to clarify the terms and problems involved in human use of multiple frames of reference, along with descriptions of route and survey, egocentric and allocentric perspectives, and reference frames, as defined and explored in cognitive science.

Next I summarize cognitive science literature that addresses the use of maps and the basic skills involved in map use, including a more focused summary of studies related to switching between frames of reference. As many of these experiments involve task-switching and types of mental rotation, I address the issue of task switching itself, as well as types of mental spatial transformations.
I discuss the hypotheses generated by this background, and the design of the experiment which attempts to build upon the literature described above using a standard mental rotation task, and a modified version of reading tasks presented in route and survey perspectives. I discuss results, in which mental rotation correlates strongly with response times on questions involving a switch in perspective, as well as males' performance on the route condition of the reading task. After discussing additional observations made in the course of completing this experiment, including a catalogue of mental rotation strategies, I then discuss how the results bear on the questions and hypotheses outlined above.

I have included a Glossary compiled of terminology gleaned from the above literature. I found this necessary since the worlds of cognitive science, philosophy, linguistics, and data visualization use similar but slightly varying terminology to discuss similar ideas, and defining these terms has been part of the process of understanding this problem. I have also included the stimuli materials, a raw data sample, and the presentation code in Appendices.
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Part I: Background

Maps and mapping technologies hold a rapidly changing place in contemporary society. The advent of Global Positioning Systems (GPS) based on satellites, has changed the way people navigate by allowing them to find their precise location on the Earth. Geographic Information Systems (GIS) have also allowed people to visualize complex information in new ways by overlaying data on maps. Similarly, a variety of everyday technologies like car navigation systems and mapping software such as Google Maps and MapQuest, have allowed people to easily generate their own maps at a variety of scales, view their environment from a birds-eye perspective, view distant locations from a 3D perspective, and possibly change their mental maps of their environments. The ability to look at a map and understand the correspondence between the map and the world is an essential part of map use, and human-computer interface research also addresses the problem of changing views in spatial information displays. Some mapping technologies also incorporate different types of perspective as well, both 2 and 3 dimensional, making the topic of navigation, map use, and perspective switching especially relevant.

Innate & Spontaneous Abilities: Developmental and Anthropological Studies

Several recent studies suggest that humans have an innate ability to use symbolic artifacts, and specifically are able to spontaneously use maps. A 2008 study by Shusterman et. al. [1] in which children were given a map and asked to place objects in a real bucket indicated by the map, showed that children around age 4 spontaneously use information in maps. The children showed similar patterns of map use to that of adults, namely when landmarks were present they neglected geometric and sense information, and paid more attention to geometrical information when landmarks were absent. This seems to show that the two types of information compete, possibly for attention. They also made the same characteristic mistakes as adults: they used angle and distance information more readily than sense information, showing similar mistakes with sense information to those of adults. Yet overall, the children correctly made use of map information without instruction regarding the relationship between the 2D representation and the 3D world. Dehaene et al. [2], performed a similar experiment with children and adults in an Amazonian indigene group that did not previously use maps. They tested
whether the subjects spontaneously detected and used geometrical information in a map task, and found results in the adults similar to the results in the children, and similar to the American children in [1].

The apparent ability of children to spontaneously use maps and other symbolic artifacts has been dubbed "representational insight," and challenged with the alternative hypothesis that these tasks do not involve an understanding of dual representation, or the ability to see something both as itself and as a symbol, but instead constitute merely a guess based on pattern matching and noticing similarities. Troseth et al. [3] examined this alternative hypothesis, and demonstrated that the ability to match a model room with a larger room appears earlier in children than the ability to use the model as a symbol. Children at 2.5 years old detected correspondences between a room and a scale model, but did not use the scale model as a map to find a toy hidden in the larger room, instead searching randomly. Three year old children did use the scale model as a symbol of the larger room. Matching ability is necessary but not sufficient: some additional skill, or representational insight, was necessary to use a symbolic representation.

Frames of Reference, Perspective, and Point-of-View

This essential insight differs from, but reflects, a necessary transformation one must make in navigating with maps: between survey experience and route experience. The way in which people give directions and describe locations can be divided into roughly two types, route and survey descriptions [4]. 'Route' and 'survey' describe ways of giving directions and describing spaces, and ways of viewing a location. A route experience can include navigating the world or a virtual environment, and route perspective descriptions and directions describe navigation in egocentric terms relative to the viewer like 'front' and 'back,' 'left' and 'right.' A survey experience is the experience of looking at a map or bird's eye perspective. Survey perspective descriptions and directions describe the world in allocentric terms, or terms relative to the environment, such as 'north' and 'south,' 'uphill' and 'downhill.' MRI results have shown activation in different brain regions when subjects navigate using route and survey strategies [8], however adults mix the two somewhat effortlessly, and have an ability to switch between the two easily [4].

The different modes of describing directions have been studied extensively in different languages and
cultures. Levinson presents a vast study of languages, and divides the frames of reference they use in describing space into three types: Relative, Intrinsic, and Absolute [5]. In this categorization, a relative frame of reference allows "for ternary relations between a referent, [what is being referred to] relatum, [what is being related to the referent], and point of view," where point of view is the origin of the primary coordinate system. Intrinsic frames of reference allow for binary relations between referent and relatum, where both the coordinate system and origin are determined by the relatum, for example a description using 'right' and 'left', based on the viewer's right and left. An absolute reference frame includes binary relations in which the origin is also fixed by the relatum, but the coordinate system is fixed by the environment. Levinson states that some cultures use primarily Absolute or primarily Intrinsic directions, and that Intrinsic requires that they also use Relative, while some languages use all three [5] pp 26, also summarized in [6].

Route and Survey perspectives are similar to categorizations of Relative and Intrinsic or Absolute frames of reference, but not quite the same thing. In a language such as English with all three frames of reference, one might tend to describe a route experience in Relative and Intrinsic terms, and a Survey experience in primarily Absolute terms, but this is not required. In addition, people who speak Absolute languages still have Route experiences, even though they might describe them entirely in Absolute terms.

Levinson, however, claims that spatial perception, and therefore behavior, is fundamentally framed and coded in the frame of reference used in the language spoken by the subject. He presents experimental evidence that people who speak languages with Absolute reference frames interpret ambiguous instructions in an allocentric way, while people who speak languages primarily Relative and Intrinsic will default to an egocentric interpretation. Therefore, with respect to the ability to switch between perspectives, he concludes that in order to share information across modalities, one must be able to either convert reference frames, or maintain one consistent one across different sensory modalities [5] also summarized in [6].

Dokic and Pacherie [6] disagree with Levinson's theory that perception's frame of reference is determined by language, but instead assert that while perception is basically egocentric, it is either free
of a reference frame or relative, which also allows cross modal sharing of information [6]. While discussing an implicitly egocentric, relative reference frame in perception, they state that Levinson's more linguistic reference frames are not essential to perception, and emphasize the distinction between perception and the way information is later processed and represented. They state that higher levels of cognitive processing might impose frames of reference in Levinson's sense. However they agree that if the origin is set at the navigator, one can possibly align the linguistic frame of reference with a perceptual one [6]. This discussion has informed the design of the stimuli in the experiment presented in Part II, in that an attempt has been made to maintain a linguistic frame of reference consistent with observations made in a relative coordinate frame with the origin set at the viewer.

Another theory called spatial framework analysis by Franklin & Tversky, summarized in [17], hypothesizes a mental scaffolding along three dimensions, used to keep track of objects as a character's orientation changes, in which "readers form a spatial mental model that consists of extensions of the three body axes, and they associate objects to it. The relative accessibility of the axes depends on characteristics of the body, characteristics of the perceptual world, and the relation of the observer to the perceptual world." In this context of experiments with reading tasks, point-of-view is defined as the viewpoint of the character in the description, while perspective is defined as the viewpoint of the reader, which may or may not be the same - depending, similar to the statement of Dokic and Pacherie [6], on where the origin is set in the description.

**Skills Involved In Map Use**
Cognitive science studies of visuo-spatial skills involved in navigation and changing frames of reference, in this case route and survey representations, might support the idea of higher levels of cognitive processing, mentioned by Dokic and Pacherie. In addition to an essential representational insight, a range of visuo-spatial skills are necessary for the ability to navigate and use maps, some of which differ depending on whether the subject is using a route or survey strategy. A variety of studies have examined skills necessary at different stages of map-reading, some focusing specifically on the differences between route and survey strategies, and some additionally focusing on the process of switching between two perspectives.
Nichols

Palermo et. al. tested a range of visuo-spatial and mental imagery skills to look for a correlation with the ability to form a mental map from navigating a virtual environment [7]. They found that the subjects' ability to make inferences from a mental map of an explored environment correlated with both the ability to rotate simple geometric shapes in two dimensions, and the ability to visualize oneself on a map. They also found a gender difference in ability to form the cognitive map. Another study [9] used a map drawing paradigm and interference with a variety of working memory skills to discover that simultaneous-visuo-spatial working memory skills seemed required for map learning, but not sequential-visuo-spatial or verbal working memory skills. Similarly, a 2008 study by Brunye et al. [12] used selective interference with a reading task involving route and survey descriptions to show that visuo-spatial and central executive functions are needed in processing mental maps, especially from route descriptions.

Other studies have looked at how route and survey descriptions differ. For example, Brunye et al. [10], with a map-drawing paradigm, found that subjects benefited from more experience reading route descriptions, while survey descriptions seem to allow formation of a mental model more quickly that did not change with further experience. This suggests that switching between the two might also be asymmetrical. While the study was not specifically focused on switching between perspectives, the subjects read route or survey descriptions and then answered questions, some of which required a switch to a new perspective, called switch questions. In some route conditions the subjects drew a map before answering survey questions, and therefore changed their perspective beforehand. Brunye reported in personal correspondence that there was a slight benefit in switch questions for those who drew the map first, although the effect was not statistically significant for this experiment.

To ask a more specific question, What is known about the process of switching perspectives? Might it also be related to types of mental spatial transformations? Zacks et al. [11] explored types of mental spatial transformations: 'object-based transformations,' or imagined rotations or translations of objects relative to the reference frame of the environment, and 'egocentric perspective transformations,' or imagined rotations or translations of one's point-of-view relative to the reference frame. Citing selective interference as well as lesion studies, they show that the types also have different chronometric properties - arguing that they are based on different neurological systems. The task
commonly called 'mental rotation' is a type of 'object-based transformation' [11]. In addition many of these studies also find gender differences in spatial ability tasks.

Some articles hypothesize that mental maps form in a reference-frame free way, regardless of the perspective in which the information is presented [13]. Others hypothesize that 1. mental maps partially retain a bias toward the perspective in which they are learned, but 2. as a mental map is used, it becomes more and more perspective-free [20]. Secondly, Franklin et al. [17] found that subjects tend to form one mental map of an environment, and to take the point of view of a described viewer. However, when the location is described from two different points of view, they seem to take a "neutral" perspective rather than switch points of view. This seems to support the theory that after changing perspectives, viewers might start to form "perspective-free" knowledge of an environment.

**Switching Perspective**

Building on the evidence that mental maps are somewhat formed relative to a learned perspective, some studies examine cognitive "switching costs" when tasks require that they switch perspective, further supporting the idea that mental maps contain some bias toward a perspective. Lee [18] demonstrated switching costs exacted while reading descriptions, as well as while verifying survey sentences and answering True/False questions. Lee explains the asymmetry in switching costs because of the extra tasks required to locate not only orientation but also point-of-view in a route description, as compared to survey descriptions. Lee concludes that "taken together the experiments suggest that switching perspective plays a significant role in comprehension that diminishes with repeated retrieval."

In the field of data visualization, a human-computer interaction study by Hollands and Ivanovic showed subjects more rapidly switched between 2D survey-perspective displays and 3D terrain displays when the transformation between the two was animated [21][21.1]. They also describe common techniques used in battlefield visualizations to mediate disorientation as: depicting landmarks across visualizations, overlapping consecutive representations, spatially representing relationships among different displays, and gradual transformations [21]. Visual landmark descriptions have also been shown to reduce switch costs when given directly prior to switching perspective in text.
These experiments study in depth when and how switching costs appear, how they can be reduced, and what skills are involved in the formation of mental maps. They have not yet examined precisely which skills perform a switching process between route and survey perspectives, and possibly also between those and forming a 'neutral' perspective. The question this study intends to answer is: What mechanism is activated when the switch occurs between route and survey? Is it a type of mental transformation? Specifically this experiment examines performance on a task of switching between route and survey perspectives, and whether it is related to mental rotation.

**Part II: Experiment**

**Hypothesis & Goals**

The switch between route and survey might be a type of mental transformation similar to object-based rotation. Because ability to form a mental map from navigation seems to correlate with simple rotation abilities, and forming a map from route experience involves a switch in reference frame, perhaps the process of switching involves a similar type of transformation. Geometrically, the process of fitting different spatial relations together into a coherent whole, and looking at a map and orienting a 'viewer' on the map seem to resemble an object based transformation. Therefore, the following experiment examines the relationship between performance on a perspective-switching task, and performance in mental rotation.

Switching perspectives can be considered a type of task-switching, a larger grouping of mental tasks hypothesized to be controlled by frontal-lobe, or higher order control mechanisms. Task switching has shown to be more difficult when performing different tasks on the same information, than when switching to an entirely new task [14], as well as exhibiting asymmetry. For example, when one task is easier or more automatic than the other, a subject might switch in one direction more quickly than the other [15]. Similarly, task-switching benefits from preparation [14], which could be one reason
switching frames of reference can result in what appears to be a perspective-free mental map. A 2005 study by Wager et al. [16], citing a theory that task switching can be divided into separate, domain-specific subsystems, lists commonly postulated subsystems as: attentional shifts, maintenance of goals and information in working memory, task scheduling and prioritization, and the mental manipulation of information in working memory, e.g. mental rotation or updating and releasing stored items. This resonates with the possibility that coordinating and/or switching perspectives could be controlled by a higher order mechanism that controls tasks like mental rotation.

Therefore, using 3D mental rotation and measures of performance and behavior on a reading task with questions, the present experiment asks primarily whether there is a relationship between the two. Additionally, it asks whether the mental maps form relative to a certain perspective, and whether additional switching lessens the switch cost over additional questions.

**Stimuli & Task Design**

**Changes Made to Existing Stimuli**

I use a reading task based on the text descriptions used in [17], [13] and [10], but have made several important changes in the stimuli. The route text descriptions included some mention of the other perspective, for example, route descriptions included a mention of a cardinal direction, in order to allow for asking questions from both perspectives. Because studies show that descriptions involving two points-of-view result in less perspective-dependent mental maps [17], by analogy, using multiple frames of reference could cause a more reference free mental model.

Therefore both non-egocentric points of view and other perspectives were eliminated from the route and survey descriptions. This was accomplished in the route descriptions by eliminating references to cardinal directions, as well as relative reference frames based on any object other than the viewer, i.e. the origin remains at the viewer throughout the description. This is in keeping with the statement mentioned earlier that an egocentric perception can be approximated with language using a relative frame of reference with the origin set at the viewer. Survey-type phrases like 'rectangular floor plan'
were also removed from the route description.

Removing cardinal directions, and all of the biases they come with from the survey description, required bigger changes. Instead of describing the environment as if from above, the text described a map of the environment. For example, "You are holding a map, and on the left of the map.." This would also serve to hold terminology constant: both survey and route descriptions use relative terminology such as 'right' and 'left.' It has been hypothesized that switch costs may partly result from a switch in terminology, therefore this holds the terminology constant while changing only the perspective of the environment, from route to survey.

Relative reference frames based on external objects were also removed from both descriptions, including other characters, and phrases related to reference frames intrinsic to other objects like "the front of the store." Viewing order of the survey perspective was edited to be more 'left to right,' while still hierarchical, the way someone would more naturally "read" a paper map, displays mentioned in the convention center description were changed to displays that were more visually distinct, after pilot studies showed that the visual similarity in the original descriptions presented an additional memory task, compared to the town, in which the objects were more different-looking.

With the elimination of the additional perspective information, an attempt was made to keep the texts entirely in one perspective, in hopes of generating a strong "switch cost."

The entirely relative route description presents a challenge in asking questions from both perspectives in order to test switch performance. To ask survey questions after subjects read a route description, subjects were instructed to imagine they had a map of the environment, oriented in a specific direction, namely "with the restrooms and cafeteria along the top of the map." This posed the question of whether the imagined map would require more rotation to align with the previously-formed mental map, for some subjects than others. Luckily, and interestingly, in pilot studies, all subjects created mental maps with the same orientation, (discussed more in Observations), and therefore the tested questions could be pre-aligned to the "imagined" map, to avoid including an additional mental rotation task.
The questions were altered to mention each object roughly the same number of times, and balance the number of true and false questions. Additionally, street names were added to the Town, some names were changed in each description, for example the River Highway became simply the Highway, because in visualizing the scene, River Highway might be unnecessarily confusable with the River, in order to avoid additional verbal memory tasks.

Twenty-four questions were presented for each stimulus as follows: Question 1 was always the same perspective as the read description. Question 2 was always in the other perspective and is therefore called the "Switch Question." After that, questions alternated between the two perspectives, such that each spatial question constituted a perspective switch from the previous spatial question, with 4 neutral questions distributed randomly among them. The spatial questions were broken down into: 10 route and 10 survey. Questions were randomized within Route, Survey, and Neutral categories.

**Reading Tasks**

The choice of a reading task to form a mental map presents the question of how reading is similar to natural navigation, if written in route perspective, and to looking at a map, if written in survey perspective. Natural navigation may involve very different strategies, such as contextual cueing, or maps that are continuously updated as a subject navigates, rather than a more enduring mental map [24]. Hegarty et al., [25] showed that standard spatial abilities tests did predict abilities in natural navigation, but more strongly predicted other indirect tests, using media other than direct experience. They concluded the skills partially overlap but are not the same skills involved in natural navigation, which operate at different scales.

Similarly, the question may arise whether the subject must interact actively with the environment to form a natural mental map. Hegarty et al. [26] examined how the source of knowledge: maps, virtual environments, and natural navigation, affected spatial memory, and concluded that the source does affect the content of the memory, but that mental maps from different sources show similar schematization and memory errors. Using virtual environments, Kehnner et al. [27] also showed that subjects' performance in spatial reasoning was independent of whether the information was gained with active or passive navigation.
The present experiment uses a passive, abstracted reading task. The subject sets their own pace but otherwise does not interact with the description. While not examining the same overall strategy used in natural navigation, the present experiment aims to test specifically the ability to switch between perspectives, which may be one of many skills involved in natural navigation. The experiences of navigating in a real environment and looking at a map, themselves, differ dramatically. A text description therefore aims to hold many factors constant: the medium, scale, senses involved, type of body movement involved, type of information learned, attention, field-of-view, familiarity, and the sequence of the information learned [26], while nonetheless allowing the subject to form a mental map of the environment from information given. Care was taken to hold constant as many factors as possible other than frames of reference used to describe the environment.

**Procedure**

Seventeen native English speakers participated, 9 women and 8 men, ages 20 to 35. All subjects were native English speakers, with a criterion of having spoken English fluently since childhood. All subjects lived in Paris, and most subjects were also multi-lingual. No subjects were eliminated based on a criterion of 6 out of 8 correct on neutral questions during the reading task. Subjects included an equal number of science or engineering and arts or humanities students. No subjects participated who had also participated in pilot studies, due to known practice effects for mental rotation [22]. Two additional subjects, one male and one female, are included in question accuracy analysis but not timing analysis, totaling 19. Eight additional subjects, 7 male and 1 female, are included in the analysis of mental rotation gender differences and strategies, totaling 25. All subjects were licensed drivers.

Subjects were given two tasks: A Perspective-Switch Task and a Mental Rotation Task, counter balanced for gender, task order, as well as for stimuli order within the Perspective-Switch Task. At the end of the study, subjects were asked debriefing questions, thanked for their participation, and then completed a 5 minute biographical survey online at their convenience.
During the Mental Rotation Task, a standard paper-based test, MRT(A) [23][22], the subjects read directions and completed 4 practice problems, then had 4 minutes to complete each of two blocks of 24 mental rotation problems, in which they matched 2 out of 4 shapes rotated around a vertical axis to a given target shape, with the possibility of a short break between blocks. They could see their time remaining on a stopwatch.

![Sample MRT(A) Problem](image)

**Figure 1.** Sample MRT(A) Problem. Target figure on the left must be matched with two rotated shapes on the right.

For the Perspective-Switch Task, subjects heard verbal instructions, then read instructions on the screen. Then they read a description of a location on a computer screen, one line at a time, at their own pace, given in either route or survey perspective.

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**Survey Description excerpt - The Town**

*On the map, the top border is made up of the White Mountain Range. Running up and down along the left side of the map is the White River.*

**Route Description excerpt - The Convention Center**

*Walking past the Books on your right, you see, again on your right, the Cameras. On your left, stretching into the corner of the building, is the Office.*

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Because mental map formation is extremely sensitive to verbal instructions [10.1][10.2][10.3],
summarized in [10], subjects were given instructions similar to those in [10] and instructed "You will be tested on your knowledge of the environment, including solving complex inference problems" both verbally and in the on-screen instructions. After reading the first passage which was either the Route Description or the Survey Description, they were instructed to press a key when ready to move on to the questions, then after additional directions, answered on-screen true and false questions about the environment by pressing 't' and 'f' keys.

After the opportunity for a short break, they read the remaining passage and answered questions, with the same procedure as the first block. Directions for questions following the Route Description instructed subjects to imagine that they had been given a map oriented in a certain direction, and that this information would remain at the top of the screen during the questions.

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True/False Question Examples - Town

Survey: *On the map, along the left side of the Town Park runs Flower Street.*
Route: *Looking out of the Store with Main Street on your right, the White Mountains are behind you.*
Neutral: *The School is the oldest structure in the town and one of the buildings around which the town was built.*

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True/False Question Examples - Convention Center

Survey: *The building's bottom wall on the map has only one display, the Laptops.*
Route: *Looking into the Children's Toys display, the Cafeteria is to your right.*
Neutral: *Several companies have decided to get together for a convention to show their products.*

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This test was administered using Matlab and an HP mini PC, as pilot studies showed that paper-based tests allowed subjects to sketch maps to help in answering questions. Reading times, response times, and answers were recorded for each question.

After the Perspective-Switch task, subjects were asked debriefing questions which included questions
about how they visualized the environments while reading and while answering questions, and asked to
draw maps of the locations. They were asked a Default Orientation Question: whether the map they
were told they were given after the route description was oriented the way they had imagined the
environment. After both tests had been completed, subjects were also asked detailed questions about
their strategies on the MRT(A). Finally, subjects were emailed a link to an online biographical survey,
containing biographical questions as well as self-assessment questions about map abilities, which they
completed at their convenience.

Results

Typical scoring for the MRT(A) gives one point only for both correct answers on a given question, for
a total of 24 possible on the test. This test used a finer grained type of scoring, in which one point was
given for each right answer, with a total of 2 possible on each question, for a total of 48 possible for the
test.

Gender
The standard Mental Rotation Test, including 25 subjects, showed a gender difference: Males missed an
average of 13.5 points out of 48, with a standard deviation of 8.2, while females missed an average of
24.3 points, with a standard deviation of 6.2. Therefore, female and male groups were analyzed
separately in comparison with data from the Perspective-Switch Task. However, no significant gender
difference was found in test score on the Perspective-Switch Task.

Controls
Out of 8 neutral control, or 'non-locative' questions, 4 on each trial, with a criterion of 6 correct, no
subjects were eliminated from the study. Performance on non-locative questions showed no relation to
performance on locative questions (n=17, t = .6). In addition, performance on non-locative questions
showed no relation with performance on MRT(A) (n=17, t = .46). No significant gender difference was
found on performance on non-locative questions. Average questions missed: male [mean, s. d.: 1, .71],
female [mean, s. d.: .56, .67].
Figure 2: Control Questions

Switch Times

The perspective switch times, or the time spent on the second question, which was the first question to require a switch in perspective, were consistently longer than average response times for each subject. Using a binomial test, \( p \) values were significant for route and survey read conditions (route \( p = .005 \), survey \( p = .094 \)). Analyzing gender separately, \( p \) values were significant for males in both survey- and route-description-read conditions (survey \( p = .031 \), route \( p = .031 \)), and for females after reading the survey description (\( p = .070 \)), but not after reading the route description (\( p = .246 \)). While a practice effect over subsequent questions, lowering the average over time, could produce these results, no decrease in response times as a function of question time was observed, neither overall nor within question categories, and therefore a practice effect did not contribute to the difference between the switch time and the average.

In examining the relationship between the switch times and mental rotation performance, and removing 2 subjects from the analysis because they acted as outliers in the route condition, a significant correlation was found between mental rotation performance and switch times after the route and survey descriptions, for both males and females. Route, males (\( n = 7 \), \( t = 2.15 \), \( p < .035 \)), females (\( n = 8 \), \( t = 2.76 \), \( p < .015 \)), Survey, males (\( n = 7 \), \( t = 2.02 \), \( p < .045 \)), females (\( n = 8 \), \( t = 2.13 \), \( p < .035 \)).
Figure 3.

Rotation vs. Route to Survey Switch

\[ f(x) = 7.8x + 17.2 \]
\[ R^2 = 0.56 \]

\[ f(x) = 13.24x - 3.81 \]
\[ R^2 = 0.48 \]

Rotation vs. Survey to Route Switch

\[ f(x) = 8.36x + 13.23 \]
\[ R^2 = 0.49 \]

\[ f(x) = 14.3x - 3.01 \]
\[ R^2 = 0.35 \]
Perspective-Switch Test Performance

Analyzing groups of questions separately - performance after reading the Route description, performance after reading the Survey description, performance on Route questions after both descriptions, and performance on Survey questions after both descriptions, many conditions showed a relationship in males, but only performance after reading the Route description correlated significantly with performance on the mental rotation task, \((n = 8, t = 1.92, p < .05)\). Females showed the least relationship with mental rotation performance on this group of questions out of all groups of questions.

Performance:
Mental Rotation vs. Route Description

![Graph showing linear regression](image)

Additional Observations

Rotation Strategies

The question also arose, "What are subjects really doing when they take the mental rotation test?"
Subjects reported a variety of strategies used to answer the questions. Even when they visualized the shape rotating, the closest strategy to the intended mental rotation, most reported either deliberately or unavoidably using additional strategies. In some cases another strategy was primary, because they found mental rotation difficult, but in other cases they used a second strategy as a check or when the
question seemed more difficult. Almost all subjects reported using more than one strategy, and they are counted once for each of the strategies they used, regardless of priority.

In addition to visualizing the shapes moving, which 17 subjects out of 25 reported doing, other strategies reported were: checking the lengths, or number of squares to a segment, and angles, e.g. 3-4-5 (9 subjects); checking to see whether the direction of the ends of the shape matched, i.e. if they were parallel or perpendicular in both the target and test shapes (8 subjects); matching an initial shape appearance (3 subjects); counting the turns on the shape (2 subjects); checking a sequence of right and left turns as if walking in the shape (2 subjects); visualizing rotating part of the shape (1 subject); imagining manually turning the object (1 subject); visualizing otherwise manually manipulating the shapes (1 subject); rotating around the shape rather than imagining the shape rotating (1 subject); counting the number of planes in the shape (1 subject); and matching within the test shapes, i.e. finding one that matched, and comparing the others to that one (1 subject). While Zacks et al. [11] stated that "some people may be more efficient at one transformation than the other, as the two processing systems should have freedom to vary independently," the subject who visualized herself rotating around the object missed a higher number of questions than average, and therefore it's not clear that the subject was necessarily using the strategy at which she is most efficient.
Mental Map Orientations

In both pilots and experimental studies, including a total of 26 subjects and incorporating descriptions of other locations not included in the final version of the study such as the Resort and the Zoo [13], all but 4 answered "yes" on the Default Orientation Question, or whether they had oriented a mental map in a certain orientation, which was verified with drawn maps. Almost all subjects oriented a mental map with the first walking direction 'up.' Two said they had not imagined a map enough for it to matter, e.g. pictured something more like a tunnel, which seemed accurate relative to their drawn maps and question performance. Only 2 subjects reported that the map had been oriented differently. Upon further questioning, one had imagined initial walking direction as 'down,' while the other had slightly misunderstood part of the text and imagined it left to right, therefore it seemed that only one subject
over all spontaneously oriented the start direction as 'down' rather than 'up.' Both subjects seemed to have been able to rotate their mental map when answering questions, and were therefore kept in the study.

**Subject Reports: Survey Accumulation, Navigation Abilities, and Non-Locative Information**

Many subjects reported that during the survey reading condition, they initially visualized a 3D world, but soon switched to visualizing a map, or that they visualized a map to begin with. Therefore, in addition to gaining a perspective-free mental map after use from multiple perspectives, their subjective reports often stated that they switched more from visualizing a 3D world to visualizing a map as they read the description, even though average response times were generally still lower for the read condition. This suggests that with shorter descriptions subjects might have maintained more of a 'route' perspective.

Subjects' self-reported navigation abilities, given by a yes/no response to a question in the biographical survey "Do you consider yourself generally good with maps and directions?" split evenly 50% yes and 50% no, and showed no relation to performance on the Perspective Switch Task overall, or the MRT(A).

Several subjects also reported ignoring the non-locative statements. As they had been instructed to remember the environment, they thought these statements were included as a type of distraction. However, despite this, no subjects missed enough non-locative questions to be removed from the study.

**Grouping**

From subjects' drawn maps, a common mistake on the Town (survey condition) map, was to move the Town Hall across a road, resulting in a map with all of the buildings on the same side of a road. This seems to show a grouping effect, a common distortion of mental maps in which subjects group associated objects more closely in space, discussed by Tversky et al. [28], and further emphasizing that subjects make schematization errors in text based tasks similar to those in visuo-spatial tasks [26].
Part III: Discussion

Experiment & Results

This experiment demonstrated a significant relationship between mental rotation ability and performance on the perspective switching task, primarily using the measure of response time on the first switch question, but additionally in males' performance on the true and false questions after a route description. A correlation between mental rotation and a perspective-switching task is in line with the possibility proposed in both cognitive science literature and linguistics and philosophy literature that changing frames of reference is controlled by a higher order mechanism, and further supports the idea that the higher order mechanism is related to systems that manipulate spatial transformations such as rotating objects.

Many past studies have demonstrated subjects' relative accuracy in self-reported abilities with maps and navigation. The lack of a relation between self reported map abilities and performance on the perspective switching task, in addition to the care taken to hold variables in the stimuli constant other than perspective on the environment, suggest that the task did test the ability to switch frames of reference, rather than the more general array of spatial abilities used in natural navigation. One can not conclude that the cost was related to a switch in terminology, or whether the stimuli were described in egocentric or allocentric frames of reference, as both were described in egocentric, relative terms, or using 'right' and 'left' with the origin based on the subject, while varying in perspective taken of the described location - a route description or a survey description. One additional slight difference is the scale of the Town and Convention Center environments, as the Town is larger than the Convention Center.

While a relationship between mental rotation and performance on true and false questions might suggest a correlation of the two skills, it's also possible that the mental rotation abilities, as shown in previous studies, aided performance by improving ability to form a mental map. Additionally, subjects could have used, and at times were observed using, verbal and other strategies to respond correctly to
the true and false questions. The gender difference shown in mental rotation but not in overall performance on the perspective switching task, suggests that while perhaps mental rotation contributes to mental map formation, those with lower mental rotation scores can use different or additional strategies to succeed at more natural navigation tasks with relatively equal ability. The significant relationship found in men, between mental rotation and the route stimuli task, along with their better average performance on mental rotation, might suggest that men are more likely to use a mental rotation strategy when faced with this task.

On the other hand, a relationship between mental rotation and switch time, normalized by the subject's average response time, and therefore measuring changes in timing instead of performance on the questions, shows stronger evidence that mental rotation correlates with switching ability.

The gender difference shown in the performance scores also brings up a question about the source of gender differences on standard mental rotation tasks. Women score lower on average, but many of the subjects in this experiment did not only use a mental rotation strategy. Do women actually perform more poorly on mental rotation, or do they tend toward other strategies that are slower or less effective? However, preference is probably a strong indicator for reliability. Subjective reports from subjects who used primarily other strategies, for example, "visualizing the blocks rotating was harder, so I counted the segments," suggest that use of other strategies may nonetheless reflect mental rotation ability. However, it could also reflect other factors such as tendency to improvise different but untested and unpracticed strategies.

While no significant decrease in response times across questions was found, it is possible that with additional controls for question length and reading time, one might emerge, therefore it is impossible to say that response times would not decrease on this task if additional noise were eliminated.

**Frames of Reference**

Supposing mental rotation were extremely highly correlated with ability to switch frames of reference, would that contribute to the additional question of whether information learned is inherently linked to a reference frame that must get matched or translated when dealing with other information, or whether
perception is separate from reference frame information, which is instead imposed at a higher level of processing? Probably not. The frame of reference could either undergo some form of translation or transformation at various stages of processing, resulting in observed switch costs.

Additionally, if switching performance were definitively not related to mental rotation, it would not necessarily mean that switching frames of reference is not a higher order control mechanism, as it could be a different mechanism.

The switch costs in this experiment however are primarily, if not entirely, due to switches in perspective on the environment, showing that switch costs are not, or not entirely, due to switches in terminology. While a switch in terminology may exact an additional cost, switch costs were shown while holding coordinate system and point of view constant, at relative and egocentric. The difference is the relation to the described location: In the Survey case, it is described as a map, which is an object one can rotate and manipulate relative to the body and the environment, but which nonetheless has an intrinsic reference frame as well. In the Route case, it was described as a three dimensional world, which one cannot rotate, but which one can rotate within or move within, relative to its intrinsic frame of reference. Both used 'right' and 'left', describing what a viewer would see, rather than an allocentric description not containing the viewer.

This relates to the above question in that switch costs, measured here with response times on switch questions, serve as an indicator of behind-the-scenes processing, and have shown that some processing is necessary to switch perspective on the environment separate from terminology used.

**Scale & Scope**

Another difference in the two perspectives is the issue of scale. In Survey perspective the subject is outside of the environment, while in Route perspective the subject operates within the environment. Including the idea of scale, and borrowing the sense of reference frame from physics, one can consider an alternative to Levinson's classification, in which all frames are the same type, all of which have both relative and intrinsic properties, used depending on the scale of the subject's experience relative to them. With a large enough difference in scale, a reference frame can be approximately absolute.
The apparent difference between different types of reference frames, reflected in both language and possibly in neural correlates, shown by different properties of different types of mental rotations, could relate to the scope of human experience relative to the scales of different frames. People have experience with moving and with objects moving or being moved, but have less direct experience with larger frames of reference such as land moving. We also have experience with intermediate reference frames, or ones in which a viewer can describe an allocentric environment that they nonetheless experience moving, including vessels like boats, which have a coordinate system of fore and aft, port and starboard. Additionally, there are internal coordinate systems smaller than the body, such as ventral and medial, proximal and distal, and frontal and dorsal. It's possible that these reference frames are not inherently different, but differ instead by the scope of the subject's experience relative to the scope of the reference frame.

When operating within the scope of a reference frame, a subject can use coordinates relative to that frame's intrinsic properties, which become allocentric. When operating from without a reference frame, a subject can use coordinates relative to that object as a whole, sometimes also oriented by the object's intrinsic properties.

Take for example an object like a globe. While operating on the Earth, 'north' and 'south' describe allocentric directions, whereas it would be unusual to refer to a lamp as 'north' of a globe, with the globe's north pointed toward the lamp, yet it would not be strange to refer to something on the globe itself, such as Africa, as 'south' of Europe, even if that 'south' were pointed toward the center of Earth, as the viewer is instead using the globe's intrinsic reference frame.

On the other hand, when operating at a large scale, if facing North from Brazil, one would not be wrong to say that Paris is to the right of Boston, but one is more likely to use terms appropriate to the scale. The Earth serves as a constant which connects both Brazil, Boston, and Paris, and thus one can linguistically traverse this distance using the Earth as a common reference frame, whereas extending the body's frame of reference to that distance, at least to English speakers, seems like more of a detached leap.
Despite the many possible frames of reference between which one can switch, perhaps the three outlined by Levinson indicate the three most fundamental scopes -- that of oneself, objects one is outside of, and the environment one is inside. Humans also easily use intermediate reference frames relative to things like boats, cars and airplanes. The breadth of Levinson's study and the variety of geography-based absolute reference frames he references can also illustrate the brain's ability to adopt different reference frames. Subjects can switch between reference frames relative to different external objects, relative to different external environments, such as going from a car to an airplane, or even internal environments, but also between the different major types, from one using a reference frame relative to an external object, to one that the subject is internal to. People can also grasp a correspondence between maps and worlds.

Therefore if one considers all reference frames to have both relative and intrinsic properties, the route and survey switch explored in this experiment, reflects a switch between one that the subject resides outside, and one that the subject resides inside. The capacity explored in the experiment, which relates to object-based transformation skills, also relates to the ability to flexibly switch between frames of reference at different scales.
Appendix A : Stimuli & Questions

Reading Instructions

The following is a short description of a location. Afterwards, you will have True and False questions about the location. To proceed to the next line of the description, press Enter. You can read at your own pace, but you can not go back to previous lines of the description. You will be tested on your memory of the environment, including solving complex inference problems.

Press Enter to Begin

Press Enter When You Are Ready To Begin Reading!

Survey Description (Condensed) - The Town

One of the largest town fairs and pumpkin festivals in the United States is held each year in the town of Etna. Etna is a typical small New England town with dirt roads and gravel sidewalks. The lay-out of the town has not changed much since it was founded in the 1700's. You are given a map and see that Etna and its surrounding areas are mostly bordered by four things: the White Mountains, the White River, the Highway, and Mountain Road. On the map, the top border is made up of the White Mountain Range. Running up and down along the left side of the map is the White River. The bottom border is made up of the Highway. Near the right side, connecting the Highway to the mountains, is Mountain Road. At the top left corner of the big intersection of the Highway and Mountain Road is the Gas Station. Most of Etna lies to the left of Mountain Road just above its intersection with the Highway. Etna is built around four streets that surround the Town Park. On the right side of the park, there is a white Patio. The Patio is used for the town band during afternoon concerts. Along the right edge of the Town Park runs Mountain Road. The other three streets in Etna are each only a block long. Along the bottom of the park runs Maple Street. Maple Street is lined with large maple trees. These maples, when they come alive with color in the fall are an attraction for many tourists. Across the street from the park, on separate sides, lie three of the town's main buildings--the Town Hall, the Store, and the School. Across Flower Street, which runs along the top side of the park, is the Store. People often gather at the Store to find out the latest town news. Across Main Street, which runs along the left side of the park, is the School. The little red, one-roomed schoolhouse is the original school built when the town was founded.

Route Description (Condensed) - The Convention Center

Several companies have decided to get together for a convention to show their products. A large convention center was chosen because it can be easily changed to accommodate the needs of various conventions. Temporary wall dividers are used to separate the display areas and to form a single entrance to each display. As you approach the building from the parking lot, you see the entrance on the left end of the building's wall near the corner, opening toward the parking lot. As you walk into the building, you see, on your left, a Bulletin Board. The Bulletin Board is used in every convention for the business cards of the participating companies. Continuing straight ahead from the entrance, where the Bulletin Board is on your left, you reach, on your right, the Books. The Books are set up so you can look through them in the display. Walking past the Books on your right, you see, again on your right, the Cameras. On your left, stretching into the corner of the building, is the Office. From the Office, you are forced to turn right and you see, to your immediate left, the Restrooms. You continue forward from the Restrooms until you see, on your left stretching into the corner of the building, the Cafeteria. The Cafeteria is privately run by a family that leases the space on a permanent basis from the Convention Center.
From the Cafeteria, you walk forward, until you are forced to turn right and you see, to your immediate left, the Bicycles display. On your right are the Televisions. Like many new television displays, you see that they are high definition televisions. You walk past the Televisions, on your right, and continue forward until you see, again on your right, the Children's Toys. On your left are the Fruit Juices. From the Fruit Juices you walk forward until you are forced to turn right and you see, to your immediate left, the Laptops. There are software samples available for potential customers to test the various Laptops. From the Laptops, you walk until you reach, on your left, the corridor leading to the entrance of the building.

**Question Instructions, Town**

Now you will see some statements that are either True or False.
Please press t if the statement is true, or f if the statement is false.
Then press Enter to go to the next question.
Do not skip any questions. Please guess if you do not know the answer.

Please answer as quickly and accurately as you can.

Press Enter.

**Questions - The Town**

**Verbatim Locative (route)**

F. 1. Driving toward the White River on the Highway, you would pass Etna on your left.
F. 2. You drive on Mountain Road a block past the Gas Station, and come to, on your right, Maple Street.
T. 3. After turning right from Main Street onto Flower Street, you see, on your right, the Town Park.
T. 4. Facing the Park from Town Hall, you see an intersection with River Highway to the left.

**Verbatim Locative (survey)**

T. 5. On the map, the top border is made up of the White Mountain Range.
F. 6. On the map, along the left side of the Town Park runs Flower Street.
F. 7. On the map, on the left edge of the Town Park, there is a white Patio.
T. 8. On the map, at the top left corner of the intersection of River Highway and Mountain Road is the Gas Station.

**Verbatim Non-locative**

T. 9. Etna is a typical small New England town.
F. 10. The School is the oldest structure in the town and one of the buildings around which the town was built.
T. 11. One of the largest town fairs and pumpkin festivals in the United States is held each year in the town of Etna.
F. 12. People often gather at the Gas Station to find out the latest town news.

**Inference (route)**

T. 13. Looking out of the Store with Main Street on your right, the White Mountains are behind you.
T. 14. Driving away from the White River on Maple Street, the School is behind you.
T. 15. Driving from the Town Hall to River Highway, you pass Maple St on your right.
F. 16. Driving toward the White Mountains on Mountain Road, the Store and the Town Hall will both be on your right.
F. 17. You turn left from Main Street onto Flower Street to reach the Store.
F. 18. Facing toward the White Mountains on Main Street, you see, on your left, the Patio.

**Inference (survey)**

T. 19. The closest building to the White River on your map is the School.
T. 20. On the map, the Gas Station is right of the river and below Maple Street.
T. 21. Directly across Mountain Road from the Patio is the Town Hall.
F. 22. The School is on a road that runs right-left on the map.
F. 23. On the map, below Flower Street is the Store.
F. 24. Across the street from the School is the Gas Station.
Question Instructions & Transition, Convention Center

Now you will see some statements that are either True or False.
Please press t if the statement is true, or f if the statement is false.
Then press Enter to go to the next question.
Do not skip any questions. Please guess if you do not know the answer.

Please answer as quickly and accurately as you can.

Press Enter.

You have been given a map of the Convention Center, with the Restroom and Cafeteria on the top wall at the top of the page.

For the following questions, imagine that you have also been given a map of the Convention Center, with the Restroom and Cafeteria on the top wall at the top of the page (you will see a reminder of this at the top of the questions, as seen above).

Press Enter to begin the questions.

Questions - The Convention Center

Verbatim Locative (route)
F. 1. As you walk into the building, you see, on your left, a Restroom.
F. 2. You walk past the Televisions, on your right, and continue forward until you see on your left, the Children's Toys.
T. 3. Walking past the Books on your right, you see, again on your right, the Cameras.
T. 4. Continuing straight ahead from the entrance, where the Bulletin Board is on your left, you reach, on your right, the Books.

Verbatim Locative (survey)
T. 5. The building's bottom wall on the map has only one display, the Laptops.
T. 6. Directly below the Cafeteria on the map, on the right wall, are the Bicycles.
F. 7. On the map, in the top left corner of the center section, with the entrance opening to the left, are the Fruit Juices.
F. 8. Right of the Bulletin Board on the map, on the right side of the building near the bottom right corner, is the Office.

Verbatim Non-locative
T. 9. Several companies have decided to get together for a convention to show their products.
T. 10. The Cafeteria is privately run by a family that leases the space on a permanent basis from the Convention Center.
F. 11. The Books are set up behind glass in the display.
F. 12. Book shelves are used to separate the display areas and to form a single entrance to each display.

Inference (route)
T. 13. Looking into the Book Display, the Bulletin Board is behind you.
T. 14. Walking from the Laptops to the Televisions, you pass, on your right, the Fruit Juices.
T. 15. Looking into the Children's Toys display, the Cafeteria is to your right.
F. 16. Walking from the Fruit Juices to the Bicycles, you pass, on your right, the Cameras.
F. 17. Walking from the Restrooms to the entrance, you pass, on your right, the Bicycles.
F. 18. Entering the building, the Office is to your right.

Inference (survey)
T. 19. On the map, the Children's Toys are right of the Books and below the Televisions.
T. 20. On the map, the Office is to the left of the Cameras.
T. 21. On the map, the Cafeteria is above and right of the entrance and above the Fruit Juices.
F. 22. On the map, below the Cameras are the Televisions.
F. 23. On the map, directly below the Office are the Restrooms.
F. 24. On the map, the Laptops are to the right of the Children's Toys and below the entrance.

**Break Between Blocks**

Please take a short break before the second half of the experiment! Press Enter when you are ready to begin reading the second part.
## Appendix B: Data Sample

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Nichols

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20 Inference Survey  47.550999  7.499420
21 Inference Survey  15.545783  9.695434
22 Inference Survey  12.999319  7.113272
23 Inference Survey  23.175516  5.780151
24 Inference Survey  17.985433  5.880875
Appendix C : Perspective-Switch Task -- Presentation Code, Matlab

Main Script: a_run (Sample)

Functions: a_open_files
reading_part
a_question_part
a_check_answers

 clear;
subj_no = '11';
readable_f = '11.txt';
stim1 = 'conventioncenterroute';
stim2 = 'townsurvey';

% STIM1
% SELECT FILES
[fid_r,fid_q,route,transition,map_reminder] = a_open_files(stim1);
% READING
t_r = reading_part(fid_r);
% ASK QUESTIONS & GET RESPONSES
[q,s_q,answers,t_q,switch_time,raw_times,ran] = a_question_part(fid_q,route,transition,map_reminder);
% CHECK ANSWERS
[correct,verbat_route,verbat_survey,verbat_non_loc,inf_route,inf_survey,tot_miss,tot_loc_miss] = a_check_answers(q,s_q,answers);
% HOUSECLEANING
ft = fclose('all');

% TRANSITION
half_screen = ['\n','\n','\n','\n','\n','\n','\n','\n','\n','\n'];
toprint = [half_screen, 'Please take a short break before the second half of the experiment! ...'
\n\n\n','Press Enter when you are ready to begin reading the second part.'];
clc; input(toprint);

% STIM2
% SELECT FILES
[fid_r2,fid_q2,route2,transition2,map_reminder2] = a_open_files(stim2);
% READING
t_r2 = reading_part(fid_r2);
% ASK QUESTIONS & GET RESPONSES
[q2,s_q2,answers2,t_q2,switch_time2,raw_times2,ran2] = a_question_part(fid_q2,route2,transition2,map_reminder2);
% CHECK ANSWERS
[correct2,verbat_route2,verbat_survey2,verbat_non_loc2,inf_route2,inf_survey2,tot_miss2,tot_loc_miss2] = a_check_answers(q2,s_q2,answers2);
% HOUSECLEANING
ft2 = fclose('all');

% PRINT RESULTS TO READABLE .TXT FILE
readable_fid = fopen(readable_f, 'wt');

fprintf(readable_fid, '%s
', 'Subject Number', subj_no);
fprintf(readable_fid, '%s
', 'Stimulus1', 'Stimulus2', 'Totals');
fprintf(readable_fid, '%s
', stim1, stim2);

read = sum(t_r); read2 = sum(t_r2);
qs = sum(t_q); qs2 = sum(t_q2);

avg_q = (qs/s_q(1)); avg_q2 = (qs2/s_q2(1));

fprintf(readable_fid, '%s
', 'Reading Time', read, read2);

avg_q = (qs/s_q(1)); avg_q2 = (qs2/s_q2(1));

fprintf(readable_fid, '%s
', 'Question Time', qs, qs2);

avg_q = (qs/s_q(1)); avg_q2 = (qs2/s_q2(1));

fprintf(readable_fid, '%s
', 'Avg Verbatim Route Time',
((sum(t_q(1:4))/4), ((sum(t_q2(1:4))/4));

fprintf(readable_fid, '%s
', 'Avg Verbatim Survey Time',
((sum(t_q(5:8))/4), ((sum(t_q2(5:8))/4));

fprintf(readable_fid, '%s
', 'Avg Non Locative Time',
((sum(t_q(9:12))/4), ((sum(t_q2(9:12))/4));

fprintf(readable_fid, '%s
', 'Avg Inference Route Time',
((sum(t_q(13:18))/6), ((sum(t_q2(13:18))/6));

fprintf(readable_fid, '%s
', 'Avg Inference Survey Time',
((sum(t_q(19:24))/6), ((sum(t_q2(19:24))/6));

fprintf(readable_fid, '%s
', 'Verbatim Route Missed',
verbat_route, verbat_route2, (verbat_route+verbat_route2));

fprintf(readable_fid, '%s
', 'Verbatim Survey Missed',
verbat_survey, verbat_survey2, (verbat_survey+verbat_survey2));

fprintf(readable_fid, '%s
', 'Verbat. Non-Locative Missed',
verbat_non_loc, verbat_non_loc2, (verbat_non_loc+verbat_non_loc2));

fprintf(readable_fid, '%s
', 'Inference Route', inf_route,
inf_route2, (inf_route+inf_route2));

fprintf(readable_fid, '%s
', 'Inference Survey', inf_survey,
inf_survey2, (inf_survey+inf_survey2));

fprintf(readable_fid, '%s
', 'Total Route Missed',
(verbat_route+inf_route), (verbat_route2+inf_route2),
(verbat_route+inf_route2+verbat_route2+inf_route2));

fprintf(readable_fid, '%s
', 'Total Survey Missed',
(verbat_survey+inf_survey), (verbat_survey2+inf_survey2),
(verbat_survey+inf_survey2+verbat_survey2+inf_survey2));

fprintf(readable_fid, '%s
', 'Total Locative Missed',
tot_loc_miss, tot_loc_miss2, (tot_loc_miss+tot_loc_miss2));

fprintf(readable_fid, '%s
', 'Raw Question Times, Question 1 Same Perspective as
Reading');
for i = 1:s_q
    fprintf(readable_fid, '%s
', raw_times(i), raw_times2(i));
end
fprintf(readable_fid,'\n%s\n', 'Questions Asked');
s_ran = size(ran);
for i = 1:s_ran(1) % usually 20, but just in case
    fprintf(readable_fid,'%d\t%d\t%d\t%d\t%d\t%d\n',ran(i,1),ran(i,2),ran(i,3),ran2(i,1),ran2(i,2),ran2(i,3));
end

fprintf(readable_fid,'\n');
for i=1:4
    fprintf(readable_fid,'%d%s\t%f\t%f\n',i,' Verbatim Locative Route',t_q(i),t_q2(i));
end

fprintf(readable_fid,'\n');
for i=5:8
    fprintf(readable_fid,'%d%s\t%f\t%f\n',i,' Verbatim Locative Survey',t_q(i),t_q2(i));
end

fprintf(readable_fid,'\n');
for i=9:12
    fprintf(readable_fid,'%d%s\t%f\t%f\n',i,' Verbatim Non Locative',t_q(i),t_q2(i));
end

fprintf(readable_fid,'\n');
for i=13:18
    fprintf(readable_fid,'%d%s\t%f\t%f\n',i,' Inference Route',t_q(i),t_q2(i));
end

fprintf(readable_fid,'\n');
for i=19:24
    fprintf(readable_fid,'%d%s\t%f\t%f\n',i,' Inference Survey',t_q(i),t_q2(i));
end

% SAVE RAW DATA TO .MAT FILE
save(subj_no); % saves all workspace variables to subj_no.mat

% HOUSECLEANING
ft = fclose('all');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% a_open_files

function [fid_r,fid_q,route,transition, map_reminder] = a_open_files (stim)

route = 0; % ON/OFF Route Variable
transition = ' ';
map_reminder = ' ';

if strcmp(stim,'townroute')
    fid_r = fopen('TownRoute.txt');
    fid_q = fopen('TownQs.txt');
    route = 1;
    transition = 'Placeholder.';
map_reminder = 'Placeholder.';
else if strcmp(stim,'townsurvey')
    fid_r = fopen('TownSurvey.txt');
    fid_q = fopen('TownQs.txt');
else if strcmp(stim,'conventioncenterroute')
    fid_r = fopen('ConventionCenterRoute.txt');
    fid_q = fopen('ConventionCenterQs.txt');
    route = 1;
    transition = 'For the following questions, imagine that you have also been
    given a map of the Convention Center, with the Restroom and Cafeteria on the top
    wall at the top of the page (you will see a reminder of this at the top of the
    questions, as seen above).\n
    Press Enter to begin the questions.';
    map_reminder = 'You have been given a map of the Convention Center, with the
    Restroom and Cafeteria on the top wall at the top of the page.';
else if strcmp(stim,'convcentsurvey')
    fid_r = fopen('ConventionCenterSurvey.txt');
    fid_q = fopen('ConventionCenterQs.txt');
else
    input ('Error.');
    return;
end
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% reading_part

function times = reading_part(fid_r)

r = [];
while (~feof(fid_r))
    g = textscan(fid_r, '%s', 1, 'delimiter', '.');
    r = [r(:); g{1}];  % e = char(r);
end;
fclose(fid_r);
s_r = size(r);

half_screen = ['\n','\n','\n','\n','\n','\n','\n','\n','\n','\n','\n','\n','\n','\n','\n'];

toprint0 = [half_screen, 'The following is a short description of a location.'...
    ',\n    'Afterwards, you will have True and False questions about the
    location.',...
    ',\n    'To proceed to the next line of the description, press Enter.',...
    ',\n    'You can read at your own pace, but you can not go back to previous lines
    of the description.',...
    ',\n    'You will be tested on your memory of the environment, including solving
    complex inference problems.',...
    ',\n    'Press Enter to Begin',
    ];
clc; input(toprint0);

toprintln1 = [half_screen, 'Press Enter When You Are Ready To Begin Reading!'];
clc; input(toprint1);

\texttt{t\_r = [];}
\texttt{for i = 1:(s\_r(1))}
\texttt{\hspace{1cm}tic;}
\texttt{\hspace{1cm}toprint2 = [half\_screen, char(r{i}),'.'];}
\texttt{\hspace{1cm}clc; input(toprint2);}
\texttt{\hspace{1cm}t\_r(i) = toc; \hspace{1cm}%% get times}
\texttt{end}

\texttt{toprint3 = [half\_screen, 'The End!', '\n\n\n',...}
\texttt{'Thank you! When you are ready to go to the questions, press Enter.'];}
\texttt{clc; input(toprint3);}
\texttt{sum\_r=sum(t\_r);}
\texttt{times = t\_r;}

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% a\_question\_part

\texttt{function \[q,s\_q,answers,t\_q,switch\_time,raw\_times,ran\] = a\_question\_part}
\texttt{(fid\_q,route,transition,map\_reminder)}
\texttt{% asks the questions}
\texttt{% raw\_answers made but not returned}
\texttt{% q = cell array: T/F answers, number, question}
\texttt{% s\_q = number of questions}
\texttt{% answers = answers given by users}
\texttt{% t\_q = time taken on each question}
\texttt{% switch\_time = time taken on second given question (not necessarily \#2),}
\texttt{% aka first switch question.}

\texttt{raw\_answers=[];}
\texttt{raw\_times=[];}
\texttt{half\_screen = ['\n','\n','\n','\n','\n','\n','\n','\n','\n'];}

\texttt{% Open File}
\texttt{q = textscan(fid\_q, '%s %s %s', 'delimiter', '.');}
\texttt{fclose(fid\_q);}
\texttt{s\_q = size(q{1});}

\texttt{% Prepare Questions, Randomize and Create Order}
\texttt{ran = [1:4 13:18; 5:8 19:24; 9:12 0 0 0 0 0]; \hspace{1cm}%% create matrix of question indices}
\texttt{\hspace{1cm}%% row 1: route}
\texttt{\hspace{1cm}%% row 2: survey}
\texttt{\hspace{1cm}%% row 3: non-locative}
\texttt{ran = Shuffle(ran); \hspace{1cm}%% randomize each column}
\texttt{s\_ran = size(ran);}
\texttt{if route == 0 \hspace{1cm}%% change the order if it's survey}
\texttt{\hspace{1cm}ran2 = ran;}

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ran(:,1)=ran2(:,2); 
rans2(:,2)=ran2(:,1);
else
dummy = 0;
end

% Give Instructions

toprint4 = [half_screen,
    'Now you will see some statements that are either True or False.',
    '
', '
', 'Please press t if the statement is true, or f if the statement is false.',
    '
', 'Do not skip any questions. Please guess if you do not know the answer.',
    '

 Please answer as quickly and accurately as you can.',
    'Press Enter.'];
clc; input(toprint4);

if route == 1 % If Route, Map Instructions First.
    toprint_in = [map_reminder, half_screen, transition];
clc; input(toprint_in);
else
    toprint_in = [half_screen, 'Press Enter to begin the questions.'];
clc; input(toprint_in);
end

% Ask Questions, Save Responses and Times
questions = q{3}; % get question vector
answers = []; t_q = []; counter = 0; a_size='t';
for i = 1:(s_ran(1))
    for j = 1:(s_ran(2))
        if (ran(i,j) > 0) % skip over 0 place holders
            counter = counter+1; % question number
            q_index = (ran(i,j)); % get the question index
            tic;
            toprint_q = [map_reminder, half_screen, char(questions(q_index)),'.

        ];
        clc;
        ans = input(toprint_q,'s'); % present question, get answer
        if (size(ans)==size(a_size)) % if they hit the wrong button by mistake
            dummy=0;
        else
            ans = input(toprint_q,'s'); % reprint the question
        end
        answers(q_index) = ans; % store t / f answer
        raw_answers(counter)=ans;
        t_{q}(q_index) = toc; % save times
        raw_times(counter)=toc;
        if counter == 2
            switch_time = toc; % save time for 2nd (first switch) question
        end
    end
end
end
eend
eend
end
toprint5 = [half_screen, 'The End!', '

Thank you!'];
clc; input(toprint5);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% a_check_answers
function [correct, verbat_route, verbat_survey, verbat_non_loc, inf_route, inf_survey, tot_miss, tot_loc_miss] = a_check_answers(q, s_q, answers)
% correct is correct answers
% other variables are numbers missed in each section

correct=[]; % see if answers were correct
correct_ans = char(q{1});
for index = 1:s_q
    response = answers(index);
    if (strcmp(correct_ans(index), 'T') && ((response==116) || (response==84)))
        % t = 116, T = 64;
        correct(index)=1;
    else if (strcmp(correct_ans(index), 'F') && ((response==102) || (response==70)))
        correct(index)=1;
    else
        % f = 102, F = 70;
        correct(index)=0;
    end
end

% misses
verbat_route = (4-sum(correct(1:4)));
verbat_survey = (4-sum(correct(5:8)));
verbat_non_loc = (4-sum(correct(9:12)));
inf_route = (6-sum(correct(13:18)));
inf_survey = (6-sum(correct(19:24)));
tot_miss = (24-(sum(correct)));
tot_loc_miss = (tot_miss - verbat_non_loc);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Glossary

Transformations & Mental Models

**Mental Rotation**: A type of object-based transformation, or visualized rotation of an external object.

**Object-Based Transformation**: Imagined rotations or translations of objects relative to the reference frame of the environment, e.g. *mental rotation*. [11]


**Representational Insight**: the appreciation of the symbolic or representational relation between two things. Suggested to also require Dual Representation by [3].

**Cognitive Maps**: Holistic mental representations of environments that can be recruited to solve novel spatial tasks. Tolman (1948).

**Dual Representation**: ability to think about the model both as an object and at the same time as a representation of something other than itself. Suggested as required for Representational Insight by [3].

**Foregrounding**: [17] "Not all information can be maintained simultaneously within a reader's focus of attention. Instead, some aspects of a narrative are foregrounded, by recency of mention or grammatical signaling devices, by importance to the reader, or by spatial proximity to the current focus of attention in the scene. Foregrounded information is accessed more quickly than background information."

**Spatial Mental Models**: Roughly the same as a 'cognitive map.' A mental model of a space, although can be at a different scale.

**Sense**: Direction or orientation, such as a direction along a line or a clockwise/counterclockwise orientation of an angle [John Mumma].

**Visual Momentum**: The user’s ability to extract and integrate data from multiple consecutive display windows (Woods, 1984), summarized in [21].
Perspective

**Perspective**: Defined for text-based tasks in [17] as "a readers viewpoint of a described scene, which may or may not coincide with a character's point of view."

**Point of View**: Defined for text-based tasks in [17] as "the viewpoint of a character in a described scene." Can be considered the same as the "origin" of a relative frame of reference.

**One-Place One-Perspective rule**: Theory proposed in [17] that readers use a single mental model containing all elements and spatial relations for a single described place, and separate models for separate places. "Readers appear to adopt a single perspective for a single model. When a single place contains only one probed observer, readers take that observer's point of view. But when a single place contains more than one character or when more than one point of view is probed, readers take a neutral perspective, not that of either point of view. When readers assume a a character's perspective, their mental models presumably contain only the objects associated with that observer; when they assume a neutral perspective, their mental models are more comprehensive, containing the objects associated with all observers."

**Perspective-Free**: (adj.) the representations that do not employ frames of reference in Levinson's sense. (Levelt 1996) summarized by [6].

**Perspective-Bound**: (adj.) representations that do employ frames of reference in Levinson's sense (Levelt 1996) summarized by [6].


**Neutral Perspective**: As used in [17], can be considered a perspective-free perspective that might contain *super-ordinate knowledge*.

**Super-Ordinate Knowledge**: Information that is not strictly linked to a perspective. [9]

Reference Frames

**Environmental Reference Frame**: The reference frame of the environment [11].

**Spatial Framework**: Summarized in [17] from Franklin & Tversky (1990), as a three-dimensional mental scaffolding, to keep track of objects as a character's orientation changes. "According to the spatial framework analysis, readers form a spatial mental model that consists of extensions of the three body axes, and they associate objects to it. The relative accessibility of the axes depends on characteristics of the body, characteristics of the the perceptual world, and the relation of the observer to the perceptual world."
Frames of Reference, [Levinson, Steven. Defined in Space in Language and Cognition.]

Referent Objects: the Referent and the Relatum
The referent is the thing being referred to, and the relatum is that which you are relating to it.

Relative: Allows for the representation of ternary relations among referent, relatum, and point of view. The origin of the primary coordinate system is the point of view and the coordinate system "seems generally to be based on the planes through the human body, giving us the up/down, back/front, and left/right set of half lines."

Intrinsic: Allows for the representation of binary relations between referent and relatum. The origin is fixed by the relatum and the coordinate system is determined by intrinsic properties of the relatum.

Absolute: The origin is fixed by the relatum, but the coordinate system is fixed by the environment.
[5], also summarized in [6].

Map Elements [Lynch, Kevin. defined in The Image of the City pp. 47-49.]

Path - "Paths are the channels along which the observer customarily, occasionally, or potentially moves. They may be streets, walkways, transit lines, canals, railroads. For many people, these are the predominant elements in their image. People observe the city while moving through it, and along these paths the other environmental elements are arranged and related."

Edge - "Edges are the linear elements not used or considered as paths by the observer. They are the boundaries between two phases, linear breaks in continuity: shores, railroad cuts, edges of development, walls. They are the lateral references rather than coordinate axes. Such edges may be barriers, more or less penetrable, which close one region off from another; or they may be seams, lines along which two regions are related and joined together. These edge elements, although probably not as dominant as paths, are for many people organizing features, particularly in the role of holding together generalized areas, as in the outline of a city by water or wall."

District - "Districts are the medium-to-large sections of the city, conceived of as having two-dimensional extent, which the observer mentally enters "inside of," and which are recognizable as having some common, identifying character. Always identifiable from the inside, they are also used for exterior reference if visible from the outside. Most people structure their city to some extent in this way, with individual differences as to whether paths or districts are the dominant elements. It seems to depend not only upon the individual but also upon the given city."

Node - "Nodes are points, the strategic spots in a city into which an observer can enter, and which are the intensive foci to and from which he is traveling. They may be primarily junctions, places
of a break in transportation, a crossing or convergence of paths, moments of shift from one structure to another. Or the nodes may be simply concentrations, which gain their importance from being the condensation of some use or physical character, as a street-corner hangout or an enclosed square. Some of these concentration nodes are the focus and epitome of a district, over which their influence radiates and of which they stand as a symbol. They may be called cores. Many nodes, of course, partake of the nature of both junctions and concentrations. The concept of node is related to the concept of path, since junctions are typically the convergence of paths, events on the journey. It is similarly related to the concept of district, since cores are typically the intensive foci of districts, their polarizing center. In any event, some nodal points are to be found in almost every image, and in certain cases they may be the dominant feature.

**Landmark** - "Landmarks are another type of point-reference, but in this case the observer does not enter within them, they are external. They're usually a rather simply defined physical object: building, sign, store, or mountain. Their use involves the singling out of one element from a host of possibilities. Some landmarks are distant ones, typically seen from many angles and distances, over the tops of smaller elements, and used as radial references. They may be within the city or at such a distance that for all practical purposes they symbolize a constant direction. Such are isolated towers, golden domes, great hills. Even a mobile point, like the sun, whose motion is sufficiently slow and regular, maybe be employed. Other landmarks are primarily local, being visible only in restricted localities and from certain approaches. These are the innumerable signs, store fronts, trees, doorknobs, and other urban detail, which fill in the image of most observers. They are frequently used clues of identity and even of structure, and seem to be increasingly relied upon as a journey becomes more and more familiar."

The image of a given physical reality may occasionally shift its type with different circumstances of viewing. Thus an expressway may be a path for the driver, and edge for the pedestrian. Or a central area may be a district when a city is organized on a medium scale, and a node when the entire metropolitan area is considered. But the categories seem to have stability for a given observer when he is operating at a given level.

None of the element types isolated above exist in isolation in the real case. Districts are structured within nodes, defined by edges, penetrated by paths, and sprinkled with landmarks. Elements regularly overlap and pierce one another.
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* Stimuli Source.


*Stimuli Source.*


* Stimuli Source.


